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(54) Producing a seismic pulse

(57) Three or more marine seismic sources (1–4) are positioned with critical inter-source spacing (D) to produce, when fired in the water, an acoustic pulse whose "primary to bubble ratio" for a given recording band width is substantially maximized. The sources of the array are adapted and positioned so that each produces when fired a bubble of substantially equal maximum radius (R). In one preferred embodiment, the array includes four sources positioned approximately at the vertices of a square having side length equal to $\sqrt{2}$ R, where R is the maximum radius of the bubble that would be produced by each source in the array if fired alone. In all embodiments, the critical spacing between each source and the source nearest thereto will be not less than 1.2 times the maximum bubble radius and not greater than the quantity 2R. In another embodiment, two or more sets of sources are employed, with the sources in each set being positioned and oriented in the water to produce when fired bubbles of substantially equal maximum radius, and such that each source in each set is separated from the other sources nearest thereto in the set by the critical spacing.

FIG. 1

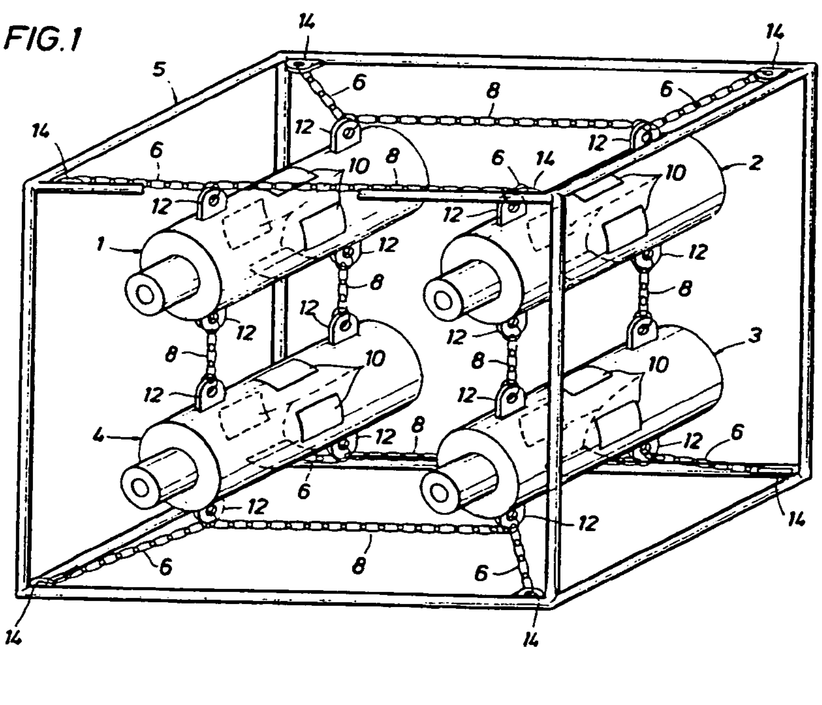

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FIG. 1

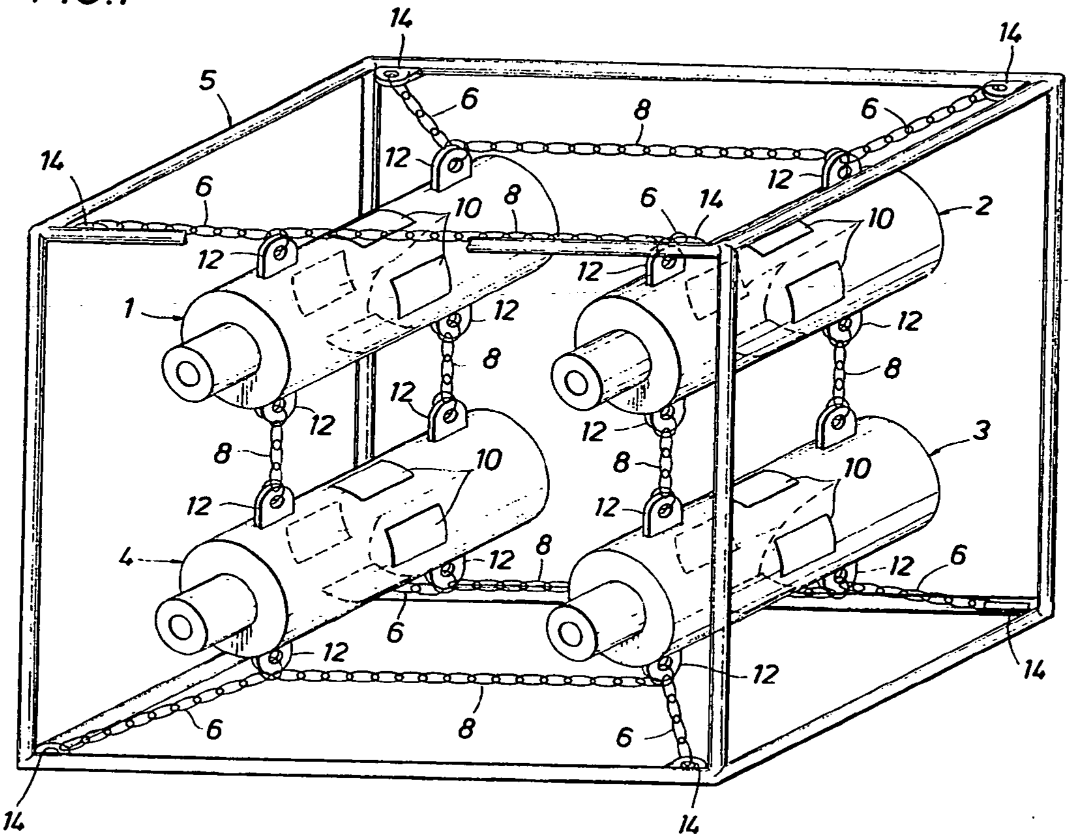
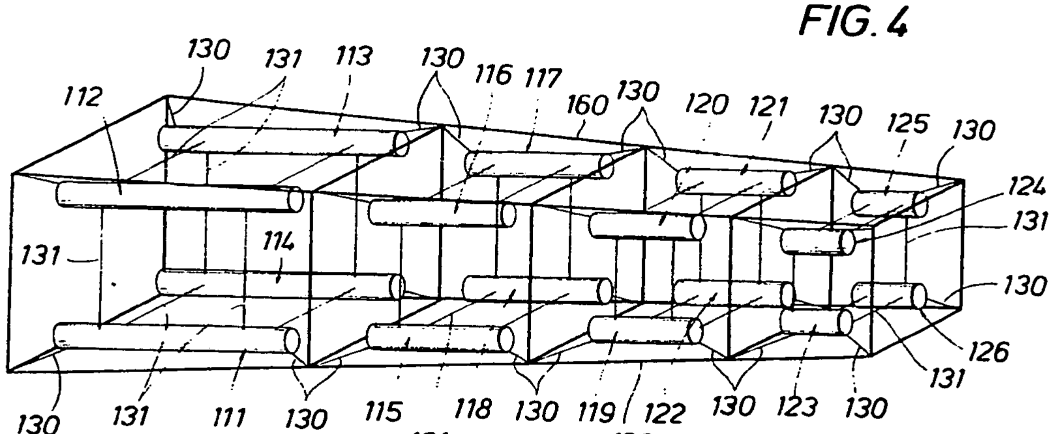

1
2
3
4
5
6
8
10
12
14

FIG. 4


111
112
113
114
115
116
117
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121
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123
124
125
126
130
131
160

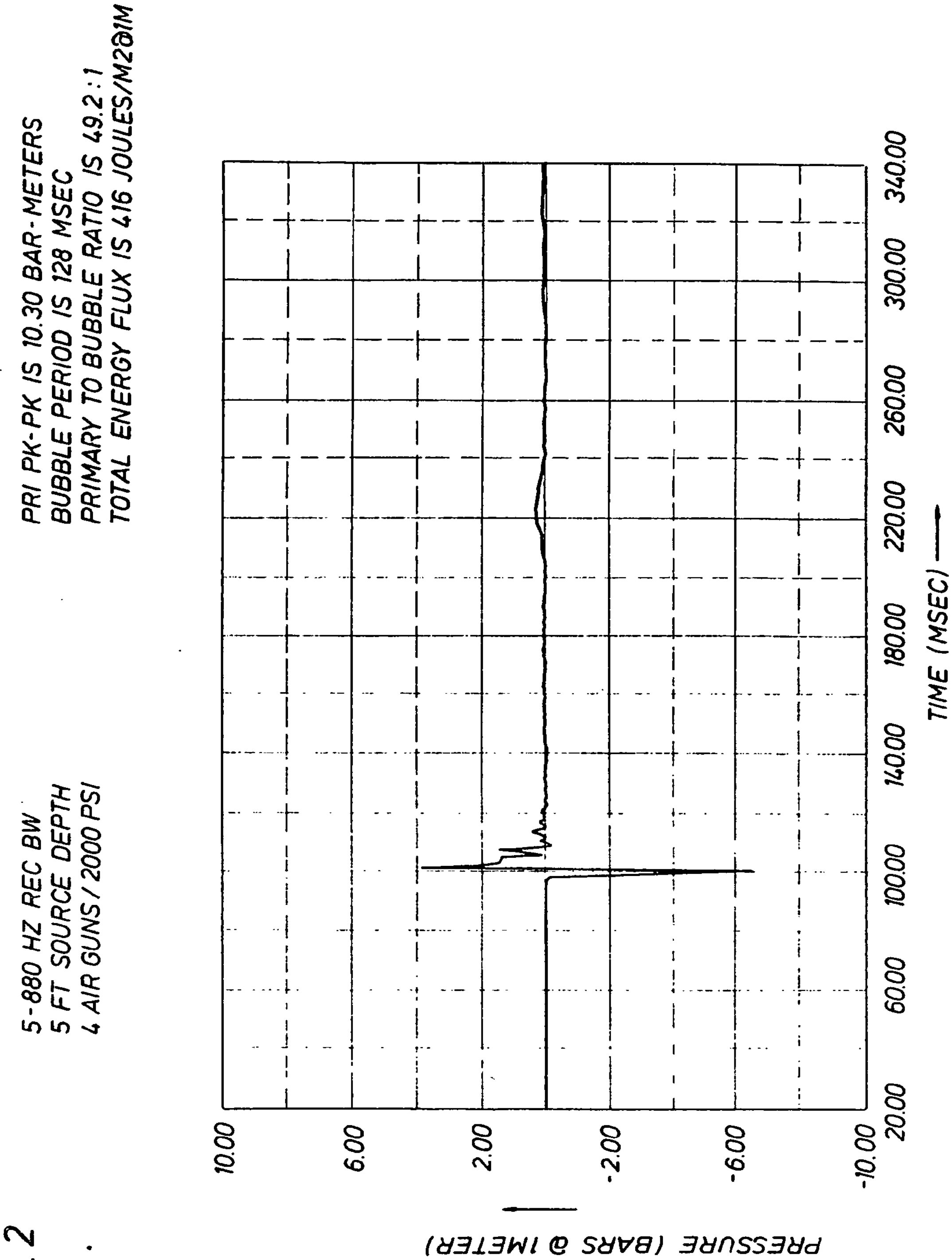

5-880 HZ REC BW
5 FT SOURCE DEPTH
4 AIR GUNS / 2000 PSI
PRI PK-PK IS 10.30 BAR-METERS
BUBBLE PERIOD IS 128 MSEC
PRIMARY TO BUBBLE RATIO IS 49.2:1
TOTAL ENERGY FLUX IS 416 JOULES/M2@1M
10.00
6.00
2.00
-2.00
-6.00
-10.00
PRESSURE (BARS @ 1METER)
20.00
60.00
100.00
140.00
180.00
220.00
260.00
300.00
340.00
TIME (MSEC)

FIG. 2

FIG. 3

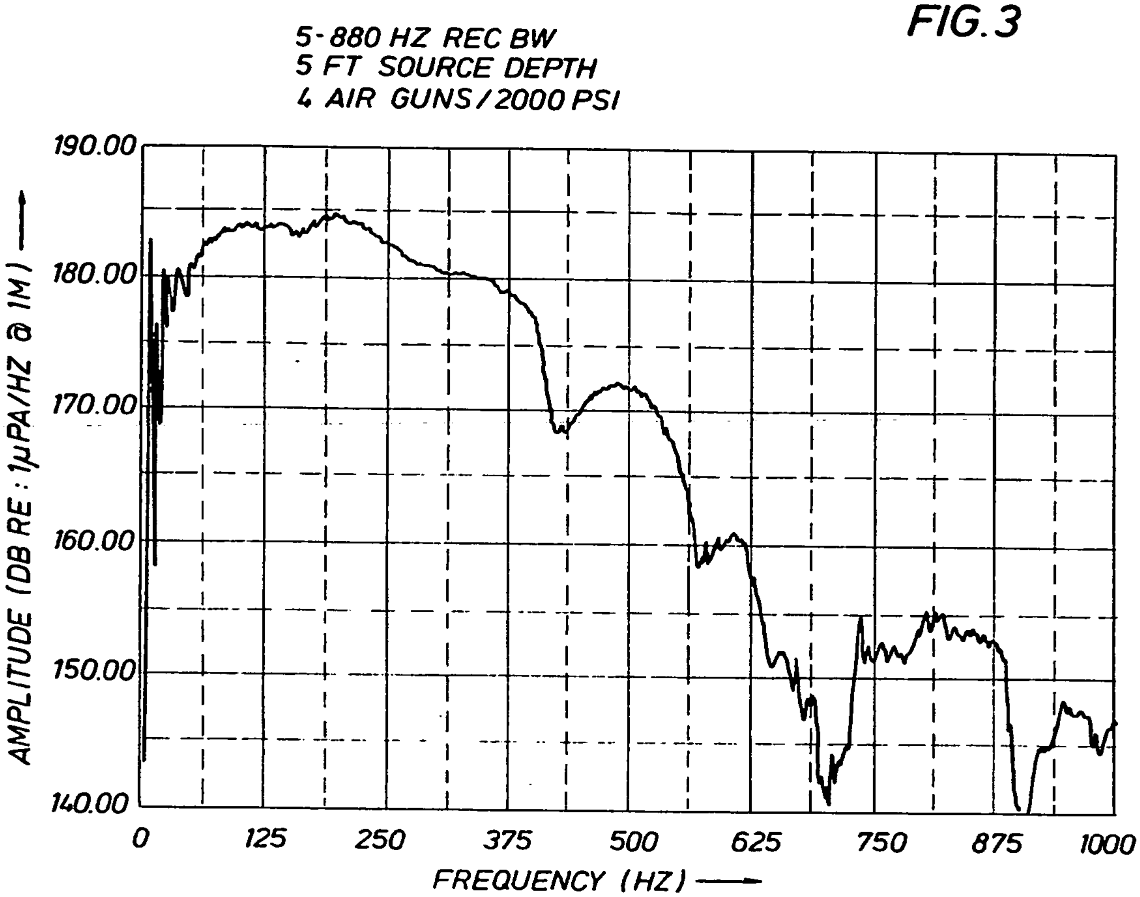
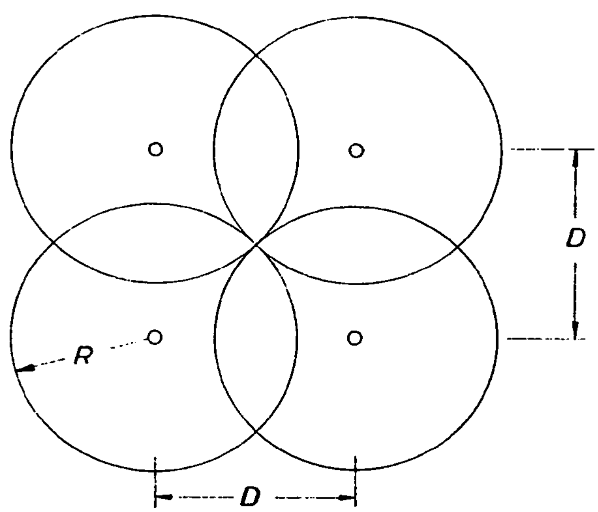

5-880 HZ REC BW
5 FT SOURCE DEPTH
4 AIR GUNS / 2000 PSI
AMPLITUDE (DB RE : 1μPA/HZ @ 1M)
190.00
180.00
170.00
160.00
150.00
140.00
0
125
250
375
500
625
750
875
1000
FREQUENCY (HZ)

FIG. 5


R
D
D

SPECIFICATION

Producing a seismic pulse

This invention relates in general to seismic prospecting. More particularly, it relates to a marine seismic source array and to a seismic pulse generation method employing marine seismic sources.

In marine seismic exploration, one or more marine seismic sources are deployed in a body of water and fired to release acoustic energy into the water to produce sonic pulses or shock waves that propagate into the subterranean geologic formations beneath the floor of the body of water. These pulses propagate through the water, into the subfloor geologic formations, and are reflected back as acoustic waves. An array of geophones, hydrophones, or like equipment detects the reflected acoustic waves and converts such waves to electronic signals. These electronic signals are recorded for subsequent analysis and interpretation. Analysis of the recorded signals can provide an indication of the structure of the subfloor geological formations and attendant petroleum accumulation in those formations.

The term "water" as used herein, including in the claims, is meant to include swamp water, mud, marsh water and any other liquid containing sufficient water to enable operation of the marine seismic sources employed in the invention.

In one method of onshore seismic exploration, a marine seismic source is placed in a shallow water pit or mud pit used otherwise for routine drilling operations. Reflected sonic pulses generated by the underwater source are detected by geophones placed on the ground. Alternatively, the geophones may be disposed downhole in a nearby well. In a variation of this technique, the reflected sonic pulses may be detected by hydrophones disposed in a water or mud pit.

There are a number of types of conventional marine seismic sources for generating a sonic pulse in a body of water. For example, explosives such as dynamite may be used to introduce strong pulses into subfloor formations. Another conventional marine seismic source utilizes the discharge of a bank of capacitors through a subsurface electrode to produce a quickly collapsing implosive gaseous bubble. This method of sonic pulse generation is commonly used when high resolution response from near-surface geologic formations is desired.

Marine seismic sources using explosive gases (such as mixtures of propane and air or mixtures of propane and oxygen) to produce a sonic pulse on ignition have gained wide acceptance. The major types of explosive gas guns include (1) those which operate by exploding a gas mixture behind a flexible membrane which in turn is in contact with the water and (2) those which operate by allowing the gas bubble produced as a result of the gas explosion to pass directly into the water. An example of the former type of gas gun is described in U.S. Patent No. 3,658,149, issued April 25, 1972 to Neal, et al. An example of the latter type of gas gun is described in U.S. Patent No. 4,193,472, issued March 18, 1980 to Kirby.

Acoustic energy sources using high pressure compressed gases instead of an explosive mixture have also achieved a wide acceptance in the industry. Typical designs for open ported compressed gas guns are found in U.S. Patent No. 3,653,460 issued April 4, 1972 to Chelminski and U.S. Patent No. 4,141,431 issued February 27, 1979 to Baird. A typical compressed gas gun for marine seismic exploration includes a housing which contains a chamber adapted to confine a charge of compressed gas at high pressure. The chamber is fitted with a valve. The valve is closed while the pressure is increased in the chamber. When the gun is "fired", the valve is rapidly opened. This allows the compressed gas to expand out of the chamber and through exhaust ports in the housing into the surrounding medium to create an acoustic pulse.

A particular compressed gas gun, the air gun, has become widely used as a marine seismic energy source. The typical air gun has the compressed gas gun configuration described above wherein the compressed high pressure gas is air. Typically, the compressed air in such air guns is maintained at pressures between 2,000 and 6,000 psi prior to release into the water to create the desired acoustic pluse.

Conventional air guns typically include a cylindrical housing containing exhaust ports through which the compressed gas is released when a valve is opened in the gun. The exhaust port configuration of these underwater compressed air guns may vary. In a common configuration, four exhaust ports are symmetrically distributed around the periphery of the cylindrical housing of the compressed gas gun PAR® Air Guns available from Bolt Technology Inc., Norwalk, Conn. are examples of air guns with four symmetrically distributed exhaust ports. In another configuration, compressed air is releas d through one exhaust port which extends 360° about the periphery of the compressed gas gun. The external sleeve air gun designed by Geophysical Services Inc. of Dallas, Texas is an example of an air gun with on such 360° xhaust port. In an external sleeve air gun, a shuttle valve concentric with the gun housing slides along the outer surface of the housing to open and close the 360° exhaust port.

Arrays of two or more marine seismic sources have long been used in performing marine

seismic exploration. For example, U.S. Patent 3,437,170, issued April 8, 1969 to Brock, et al., describes a technique for simultaneously firing several marine seismic sources in an array. In accordance with the Brock, et al. technique, the energy frequency spectrum of the acoustic signal produced by the array is shaped by generating at each source a bubble, some of which bubbles coalesce while others do not. The coalesced bubbles each generate different frequency components in the energy frequency spectrum than the individual bubbles which coalesced to form them would have done, if they had not coalesced. Brock, et al. does not disclose any method for improving suppression of the strength of the successive oscillations of any of the bubbles produced relative to the strength of the initial or "primary" component of the acoustic signal produced. In particular, Brock, et al. neither teaches nor suggests any preferred critical spacing of sources for improving the amplitude ratio of the primary signal component of the generated signal to the strongest of the accompanying successive oscillation components of the signal. This amplitude ratio will sometimes be referred to hereinafter as the "primary to bubble ratio".

Arrays designed to suppress secondary bubble oscillations relative to the primary signal produced thereby have been proposed. For example, U.S. Patent 4,382,486, issued May 10, 1983 to Ruehle describes, an air gun array in which the volume ratios of the air guns and the inter-gun spacings are selected so as to reduce acoustic noise due to secondary bubble oscillations while satisfying the constraint that the overall array dimensions are sufficiently small so that the array constitutes a "point source". Ruehle teaches that the individual guns of the array should be spaced sufficiently far apart so that the bubbles produced thereby are independent and do not interact, and also teaches that the array should be "tuned" to reduce acoustic noise due to bubble oscillations by selecting the ratios of the air gun volumes in accordance with a specified equation.

Another array design employing both single air guns, and clusters of equal volume air guns with each gun in a cluster spaced sufficiently closely to the other guns in the cluster so that the bubbles produced thereby coalesce, has been proposed for generating an acoustic pulse whose primary to bubble ratio exceeds that of the acoustic signal which would be produced by replacing each cluster with a single air gun of volume equal to the sum of those in the cluster. This combination of single guns and clusters of guns is described as necessary to produce an improved total array response. For a description of such an array, see B. F. Giles, et al., "System Approach to Air-Gun Array Design," Geophysical Prospecting, 21, pp 77–101 (1973), and W. R. Cotton, "The Application of External Sleeve Guns to Marine Source Arrays," presented at the 46th Meeting of the European Association of Exploration Geophysicists, London, U.K. June 19–22, 1984. However, the prior art does not disclose or suggest, and it has not been hitherto known that if sources adapted to produce bubbles having substantially identical maximum radii are separated by the critical distance described in this application, the resulting acoustic pulse will have an unexpectedly large primary to bubble ratio (reaching as high as 49:1 with a recording band width of 5–880 Hz under conditions to be described in detail below) and will be particularly useful for seismic exploration when deployed at shallow depths, such as depths of less than ten feet.

Another array design for reducing secondary bubble oscillations is described in U.S. Patent 2,771,961, issued November 27, 1956 to Blake, Jr. The Blake, Jr. array includes two explosive charges of specified relative potential energy, separated by a sufficiently large vertical distance so that the explosive bubbles produced are prevented from coalescing. Blake, Jr. teaches that the preferred vertical spacing, D, of the charges, should satisfy the relation $(A_1+A_2)\leq D\leq 3/2\,(A_1+A_2)$, where A_1 is equal to the maximum radius of the explosive bubble from the first charge, and A_2 is equal to the maximum radius of the explosive bubble from the second charge. Blake, Jr. teaches that this array configuration will result in dissipation of energy in the secondary bubble oscillations due to interaction between the two explosive bubbles. An array of explosive charges having the vertical separation taught by Blake, Jr. would be unsuitable for use in exploration operations in shallow water and would not produce a suitable acoustic signal for exploration operations requiring a broadband signal with substantial energy content in the frequency range approaching 250 Hz.

According to the invention from one aspect there is provided a method of producing a seismic pulse in a body of water, including the steps of:

(a) disposing in the water a set of at least three marine seismic sources, each adapted to produce in the water a gas bubble having maximum radius substantially equal to the same quantity R, where the sources are disposed at depths such that each produces, when fired, a bubble of maximum radius R, and the sources are disposed such that each source is separated from each of the nearest sources thereto in the set by a critical distance, D, where $1.2R\leq D\leq 2R$ and D is selected, within the stated range, so as substantially to maximize suppression of the successive oscillations of the acoustic signal resulting from firing the sources relative to the primary pulse thereof; and

(b) firing the sources substantially simultaneously to produce a seismic pulse in the water.

According to the invention from a second aspect there is provided an array of marine seismic sources for producing a seismic pulse in a body of water, comprising:

—a set of at least three marine seismic sources, each source being capable of producing in the water a gas bubble having substantially the same maximum radius substantially equal to R; and

—a positioning unit adapted to position the set of sources in the water so that each source in the set produces, when fired, a bubble of maximum radius R at a depth L in the water, and each source in the set is separated from each of the sources nearest thereto in the set by a critical distance D, where $1.2R \leq D \leq 2R$, and D is selected, within the stated range, so as substantially to maximize suppression of the successive oscillations of the acoustic pulse resulting from substantially simultaneous firing of the sources in the set relative to the primary pulse thereof.

We characterize the sources of the seismic source array as "interdependent" when separated by the critical spacing. In one preferred embodiment, the array includes four sources positioned approximately at the corners of a square having sides of approximate length $\sqrt{2}$ R. In another preferred embodiment, the array includes three sources positioned approximately at the vertices of a horizontal triangle having two sides of approximate length $\sqrt{2}$ R.

The simultaneous firing of the sources in the described array is particularly advantageous where the bubbles are produced at source depths less than about ten feet.

The invention will be better understood from the following description, given by way of example and with reference to the accompanying drawings, wherein:

Figure 1 is a perspective view of one form of marine seismic source array in accordance with the invention. The array includes four air guns held at a desired critical spacing with respect to each other and a frame to which the guns are attached.

Figure 2 is a graph showing the time domain characteristics of an acoustic pulse generated in accordance with a preferred embodiment of the invention using an array of four air guns, each having 40 cubic inch volume and operated at 2000 psi, to produce bubbles at a depth of five feet in a body of water.

Figure 3 is a graph showing the frequency domain characteristics of an acoustic pulse resulting from operation of the same array employed to generate the pulse characterized in Fig. 2.

Figure 4 is a simplified perspective view of an alternative embodiment of the inventive array which includes four sets of four sources. Each four-source set is of the type shown in Fig. 1.

Figure 5 is a schematic drawing showing four bubbles, each having maximum radius equal to R. Each bubble has been produced by firing one of the marine seismic sources in an embodiment of the inventive array including four sources disposed at the vertices of a square having side length D, equal to $\sqrt{2}$ R.

The marine seismic apparatus includes three or more marine seismic sources, each adapted to produce a bubble of maximum radius R, when the source is deployed in the inventive array and fired in a body of water. Commercially available air guns of substantially equal volume and charged at substantially equal pressure would be suitable for use in a preferred embodiment of the invention. The embodiment shown in Fig. 1 includes four such substantially equal volume air guns (identified as air guns 1, 2, 3, and 4). Each of the air guns includes one or more exhaust ports 10 for permitting release of gas in directions away from the longitudinal axis of the gun. Flanges 12 extend from each gun for use in connecting the gun to other guns or to support structure 5. Chains 8 or the like are attached between pairs of flanges 12 to connect guns 1–4 together. Chains 6 or the like are attached between flanges 12 and 14, extending out from structure 5, to connect guns 1–4 to structure 5. Structure 5 is capable of being connected to a marine support structure such as a boat, barge, buoy, float, dock, pier, or wharf to support structure 5 in a desired position relative to the surface of the water. Structure 5, chains 6 and 8, and flanges 12 and 14 will sometimes hereinafter be collectively referred to as a "positioning unit." It will be apparent that many other types of positioning units may alternatively be employed to hold the air guns of the array in a desired position relative to each other and to the water surface.

The positioning unit should be suitably dimensioned and oriented with respect to the water surface so that the sources of the array will each produce a bubble of maximum radius approximately equal to R in the water when fired, and that each source is separated by the critical distance, D, from each of the other sources in the array nearest thereto. Preferably in the Fig. 1 embodiment including four sources arranged at the four corners of a square, each source is separated from the sources nearest thereto by critical distance D, where D is approximately equal to the quantity $\sqrt{2}$ R. In one mbodiment, the square will be oriented in the water so as to produce bubbles centered initially at a common depth L in the water.

It is not essential that ach bubble produced by a source of th inventiv array b centered initially in the same horizontal plane (i.e. at a unique depth). Rather, the sources may be disposed in the water when fired so that the difference in depth between the initial positions of the centers of the individual bubbles is sufficiently small so that the maximum radius of each bubble produced is substantially the same. Thus, for example, it is possible to employ an array

similar to that of Fig. 1 where the longitudinal axes of guns 1 and 2 (i.e. the axes about which ports 10 are concentrically positioned) are disposed at a different depth than are the longitudinal axes of guns 3 and 4, provided that the maximum radius of each bubble produced is substantially the same. For another example, it is possible to employ an array similar to that of Fig. 1 where ports 10 of guns 1, 2, 3, and 4 are all disposed substantially at the same depth when the guns are fired, provided that the maximum radius of each bubble produced is substantially the same.

We have found that the acoustic pulse produced by the source array, in the embodiment shown in Fig. 1, is essentially unaffected by rotation of one or more of the guns of the array, provided that after rotation the guns are disposed in a new position such that the distances between the centers of the bubbles initially produced by the guns are substantially the same as before the rotation.

It will be understood that the magnitude of the maximum bubble radius R will depend on a variety of parameters, including the depth L at which the bubble is initially centered, and the characteristics of the associated marine seismic source. It is contemplated that seismic sources other than air guns may be employed in the inventive apparatus. In a preferred embodiment in which air guns are employed, the magnitude of R will depend, in a manner well known in the art, on the gas chamber volume and the pressure of gas in the chamber immediately prior to the gun firing. See, for example, the "Seismic Energy Sources 1968 Handbook," prepared by Staff Members of United Geophysical Corporation and presented at the 38th Annual Meeting of the Society of Exploration Geophysicists, Denver, Colorado, October, 1968, for an explanation of how the maximum bubble radius R may be estimated from known air gun characteristics.

We have found that in an array including four air guns, of the external sleeve type and having pressurized gas chamber volume equal to 40 cubic inches and charged at 2000 p.s.i., the optimal array configuration for operation at a depth of five feet (i.e., so as to produce bubbles initially centered at a depth of approximately five feet) in water is to dispose the sources at the vertices of a square of side length approximately 22–1/2 inches. Table 1 shows the average estimated primary to bubble ratios (associated with a recording band width of 5–880 Hz) of such an array, operated at depths 20, 15, 10, and 5 feet, respectively.

Table 1.

Depth (ft.) \ Guns Fired	1,2,3 and 4	1,2 and 3	1 and 2	1 and 3	1
20	12	10	9	5	3
15	13	12	10	7	4
10	25	17	13	10	6
5	45	28	20	13	10

The array used to generate the data of Table 1 was of the type shown in Fig. 1 with an external sleeve gun replacing each of the four-ported air guns shown. The left-most column of Table 1 contains data resulting from simultaneous firing of all four guns shown of the array. The column second from the left contains data resulting from simultaneously firing guns 1, 2, and 3 (as identified in Fig. 1) only. Similarly, the other columns contain data resulting from simultaneously firing guns 1 and 2, 1 and 3, and 1 alone. The array was disposed in the water with orientation such that the longitudinal axis of each gun was vertical and the gas release ports of the guns were disposed horizontally with respect to each other at the designated depth.

Fig. 2 shows the time domain characteristics of an acoustic pulse generated by simultaneously firing the guns of the array used to collect the Table 1 data when the gas release ports of the guns were disposed at a depth of five feet. The horizontal axis shows the time elapsing after firing (in milliseconds), with firing occurring at t=100 msec. The curve shows acoustic signal pressure versus time received at a detector located 183 meters below the source array, normalized to equivalent pressure as if measured at a distance of one met r, in a manner commonly used in the industry.

Fig. 3 shows the frequency domain characteristics of an acoustic pulse generated in the same manner, with the same array, as was the pulse whose time domain characteristics are shown in Fig. 2. Of particular interest is the smooth broad bandwidth indicated by the amplitude spectrum shown. We have found that it is preferable to deploy and fire the air guns of the inventive array at depths of ten feet or less to achieve much better temporal resolution than obtainable with conventional air gun arrays. At such shallow depths, the ghost notch will appear at a frequency not less than 250 Hz, and 1 millisecond recording is the minimum acc ptable standard for optimal use of the source array.

Fig. 5 shows schematically four bubbles superimposed on each other, where each has been produced by firing one of the sources of an embodiment of the inventive array. Each bubble is shown at the moment at which it has expanded to its maximum radius, R. The sources of the Fig. 5 array are disposed at the four vertices of a square having side length equal to $\sqrt{2}$ R. It is apparent from the regions of bubble overlap, that if the four sources of the array are fired substantially simultaneously, the four resulting bubbles will interact significantly.

Arrays including more than or less than four marine seismic sources or just three sources are also possible alternative embodiments. For example, in one of the preferred embodiments, three sources are employed, each capable of producing a bubble of maximum radius R in the water. In this alternative preferred embodiment, the three sources are held by a positioning unit so that each produces, when fired, a bubble of maximum radius R, and the sources are disposed approximately at the vertices of a triangle having two sides of length $\sqrt{2}$ R. It is also possible that the three sources be disposed so that the bubbles produced thereby when fired have centers initially positioned approximately at the vertices of a triangle, where at least two sides of the triangle have length D in the range $1.2R \leq D \leq 2R$.

A preferred embodiment of the three-source array may be produced by removing one gun of the Fig. 1 array and simultaneously firing the other three. It is also possible that only three of the four guns of the Fig. 1 array be simultaneously fired, while the fourth is not fired. Improved secondary pulse suppression is achieved if the preferred inter-gun spacing described above is maintained. For example, the data of the second column of Table 1 shows that a pulse with primary to bubble ratio equal to 28:1 may be achieved with the three gun embodiment of the invention.

It is also possible to employ arrays with more than four sources, where the sources in the array are positioned so as to produce equal volume bubbles (with maximum radius R) and each source in the array is separated from the sources nearest thereto by the critical distance described herein. In one embodiment, six sources are positioned in two parallel rows of three, where the distance between each source and the nearest sources thereto is approximately $\sqrt{2}$ R.

The optimum critical spacing in each embodiment will depend on the specific characteristics of the sources and the type of positioning unit employed to position the sources as desired. In operation, it is preferred that for a given array, the optimum critical inter-source spacings be determined experimentally by performing several sequential measurements with different inter-source spacings selected from within the range between 1.2R and 2R, inclusive. Maximum primary to bubble ratio for a given recording band width will be achieved at the optimum critical spacing.

It is also possible to employ arrays including two or more "sets" of sources, where each set itself embodies the inventive array. For example, the embodiment shown in Fig. 4 includes four sets of sources, each of the four-source type shown in Fig. 1. The first set of sources includes 111, 112, 113, and 114. The other three sets of sources include, respectively, sources 115–118, 119–122, and 123–126. The sources are positioned in a desired position with respect to frame 110 by chains 130 or the like, and the sources within each set are positioned as desired with respect to each other by chains 131 or the like.

In one variation on the Fig. 4 embodiment, the array includes air guns of approximately equal volume and charged at approximately equal pressure, and is oriented in the water so that the sources produce bubbles initially centered at depths within a sufficiently narrow range so that the maximum radius of the bubbles produced by the individual sources of the array are substantially the same. In another variation, each set of sources of the array includes air guns of approximately equal volume and charged at approximately equal pressure (the volume and pressure of the air guns may differ from set to set, or may be equal for all the sets in the array), and the sets are held in position by a positioning unit differently dimensioned than the unit shown in Fig. 4 so that the bubbles produced by the sources of a first set are produced at a different average depth than are the bubbles produced by sources in a second set. In this latter variation, the bubbles produced by sources in the first set may have a different maximum radius than do the bubbles produced by sources in the second set, or may have the same maximum radius as do the bubbles produced by sources in the second set. It is also possible that each set include sources of a variety of different types (such as, for example, air guns of different volume), provided that the sources in each set all produce, when fired, bubbles of substantially identical maximum radius (this maximum radius may differ from set to set) and the sources in each set are separated by the critical spacing associated with that maximum bubble radius. Frame members 160, connecting the individual sets of sources, will preferably have sufficiently short length so that the array will have the characteristics of a point source. For some applications, the lengths of frame members 160 may be selected so that the sets of sources are predominately independent.

The maximum bubble radius associated with the sets of sources may be identical, or alternatively, may differ from set to set. In one embodiment sets of air guns are employed, with each

set including air guns of a common volume where the volume ratios of the sets are determined in accordance with any known technique for tuning air gun arrays.

In operation of any of the array embodiments described herein, an acoustic pulse, whose bubble oscillations are suppressed relative to the amplitude of the primary pulse component of the acoustic pulse, is produced in the water by firing the interdependent sources of the array substantially simultaneously so as to maximize the amplitude of downward-traveling energy in the primary pulse. For example, in an embodiment of the seismic source array having three sets of sources with each set disposed at a different depth, but such that all the sets produce, when fired, bubbles centered at depths within a ten foot range, the sources will preferably be fired at selected times within a period of approximately two millisecond duration. In this example, where the three sets are disposed to produce respectively, bubbles centered at depth L, (L−5 feet), and (L+5 feet), the set will preferably be sequentially fired at intervals of one millisecond.

CLAIMS

1. A method of producing a seismic pulse in a body of water, including the steps of:

(a) disposing in the water a set of at least three marine seismic sources, each adapted to produce in the water a gas bubble having maximum radius substantially equal to the same quantity R, where the sources are disposed at depths such that each produces, when fired, a bubble of maximum radius R, and the sources are disposed such that each source is separated from each of the nearest sources thereto in the set by a critical distance, D, where $1.2R \leq D \leq 2R$ and D is selected, within the stated range, so as substantially to maximize suppression of the successive oscillations of the acoustic signal resulting from firing the sources relative to the primary pulse thereof; and

(b) firing the sources substantially simultaneously to produce a seismic pulse in the water.

2. A method as claimed in claim 1, wherein the sources are air guns having substantially equal chamber volumes which are operated at substantially equal pressure.

3. A method as claimed in claim 1 or 2, wherein the set of sources includes four sources disposed so that the four bubbles produced thereby have centers initially positioned approximately at the four vertices of a square.

4. A method as claimed in claim 3, wherein distance D is approximately equal to the quantity $\sqrt{2}$ R.

5. A method as claimed in claim 1 or 2, wherein the set of sources includes three sources disposed so that the three bubbles produced thereby have centers initially positioned approximately at the three vertices of a triangle, where at least two sides of the triangle have length equal to $\sqrt{2}$ R.

6. A method of producing a seismic pulse in a body of water, including the steps of:

(a) disposing in the water a first set of at least three marine sources, each adapted to produce in the water a gas bubble having maximum radius substantially equal to the same quantity R, where the sources in the first set are disposed at depths such that each produces, when fired, a gas bubble of maximum radius R, and the sources are disposed such that each source in the first set is separated from each of the nearest sources thereto in the first set by a critical distance D, where $1.2R \leq D \leq 2R$, and D is selected, within the stated range, so as substantially to maximize suppression of the successive oscillations of the acoustic pulse resulting from firing the first set of sources relative to the primary pulse thereof;

(b) disposing in the water a second set of at least three marine seismic sources, each adapted to produce in the water a gas bubble having maximum radius substantially equal to the same quantity S, where the sources in the second set are disposed at depths such that each produces, when fired, a gas bubble of maximum radius S, and the sources are disposed such that each source in the second set is separated from each of the nearest sources thereto in the second set by a critical distance E, where $1.2S \leq E \leq 2S$, and E is selected, within the stated range, so as substantially to maximize suppression of the successive oscillations of the acoustic pulse resulting from firing the second set of sources relative to the primary pulse thereof; and

(c) firing the sources in both sets substantially simultaneously to produce a seismic pulse in the water.

7. A method as claimed in claim 6, wherein each source in the first set is an air gun having substantially the same chamber volume as the other sources in the first set, and each source in the second set is an air gun having substantially th same chamber volume as the other sources in the second set.

8. A method as claimed in claim 6 or 7, wherein the maximum radius R is substantially equal to the maximum radius S.

9. A methods as claimed in any preceding claim, wherein the marine seismic sources are disposed in the water at a depth of not more than about ten feet below the water surface.

10. An array of marine seismic sources for producing a seismic pulse in a body of water, comprising:

—a set of at least three marine seismic sources, each source being capable of producing in

the ater a gas bubble having substantially the same maximum radius substantially equal to R; and —a positioning unit adapted to position the set of sources in the water so that each source in the set produces, when fired, a bubble of maximum radius R at a depth L in the water, and each source in the set is separated from each of the sources nearest thereto in the set by a critical distance D, where 1.2R≤D≤R, and D is selected, within the stated range, so as substantially to maximize suppression of the successive oscillations of the acoustic pulse resulting from substantially simultaneous firing of the sources in the set relative to the primary pulse thereof.

11. An array as claimed in claim 10, wherein:
—the set includes four marine seismic sources, and the distance D is substantially equal to $\sqrt{2}$ R.

12. An array as claimed in claim 10, wherein:
—the set includes three marine seismic sources, and the sources are disposed approximately at the vertices of a triangle, where at least two sides of the triangle have length equal to $\sqrt{2}$ R.

13. An array as claimed in any one of claims 10 to 12, further comprising:
—a further set of at least three marine seismic sources, each source in the second-mentioned set being capable of producing in the water a gas bubble having substantially the same maximum radius substantially equal to S; and
—a further positioning unit adapted to position the sources in the second-mentioned set such that each source in the second-mentioned set produces, when fired, a bubble of maximum radius S at a depth M in the water, and each source in the second-mentioned set is separated from each of the sources nearest thereto in the second-mentioned set by a critical distance E, where 1.2S≤E≤2S, and E is selected, within the stated range, so as substantially to maximize suppression of the successive oscillations of the acoustic pulse resulting from substantially simultaneous firing of the sources in the second-mentioned set relative to the primary pulse thereof.

14. An array as claimed in claim 13, wherein:
—the first and second-mentioned sets are so arranged that the bubbles produced by the sources in the first-mentioned set are predominately independent of the bubbles produced by the sources in the second-mentioned set.

15. An array as claimed in claim 13 or 14, wherein:
—the maximum radius R is substantially equal to the maximum radius S.

16. An array as claimed in claim 13 or 14, wherein:
—the maximum radius R is substantially different than the maximum radius S.

17. A method of producing a seismic pulse in a body of water, substantially as hereinbefore described with reference to Figs. 1 to 3 or 5, or the modification of Fig. 4, of the accompanying drawings.

18. An array of marine seismic sources, substantially as hereinbefore described with reference to Figs. 1 to 3 or 5, or the modification of Fig. 4, of the accompanying drawings.

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